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Trends of Fiber-Optic Microcellular Radio Communication Networks

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SUMMARY Exploitation of air interfaces for mobile communications is rapidly increasing because of diversified service demands, technology trends and radio propagation conditions. This paper summarizes the radio and optic interaction devices and systems that can solve the future problems resulting from spreading demands in mobile multimedia communications. The concept of the Virtual Free Space Network (Radio Highway Network) is proposed for universal mobile access networks that can support any mobile service or radio air-interface. As one example of the proposed network, the optical TDMA network for radio is analyzed and results of some theoretical calculations are shown.

key words: *mobile communications, virtual radio free-space network, radio highway, optics and microwave interaction, optical TDMA*

1. Introduction

Recently, the optical technology has made very large impacts on communication systems such as high-speed digital trunk transmission links, access networks and subscriber loops in the multimedia era. At the same time, radio technology has realized modern mobile communications such as digital cellular, personal handy phone systems and future public land mobile telecommunication systems. These technologies are presently used separately in their own application areas; however, if they were used synergistically, they could open new application worlds and bring us even greater benefits. One example of the new application world is the universal and simple radio access networks for various types of diversified mobile services, which we have named Fiber and Radio Extension Link (FREx link) and Radio Highway Networks. Benefits would include low prices and seamless operation for the rapidly growing future multimedia mobile services in which various types of air interfaces will be used.

From the user's perspective, various new synergistic benefits can be obtained from combined technologies. However, from the technological stand point, we should plan to resolve not only the problems that exist in each technology, but also new unexpected problems. This will require novel breakthroughs.

In Sect. 2, research and development activities in Optomicrowave Interaction devices and applications are reviewed. Section 3 describes the present status of mobile services and problems, and offers FREx link as one solution. Millimeterwave-over-fiber technology is also reviewed. Section 4 describes future prospects and some proposals for the Radio Highway Networks and Virtual Radio Freespace. Finally, we provide realizable configurations and performance calculation results.

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2. Present Status of Optomicrowave Interaction Device and Applications

2.1 Research Areas of Optomicrowave Interaction Technology

Optomicrowave interaction device technologies are divided into two groups; one is optical signal control by microwave or electrical signals, and the other is microwave signal control by optics. The former group is represented by optical modulators and optical switches, and have mainly been researched by optical device engineers. Here, the electrical signal exists near the baseband signal. Products of this research have been applied to high-speed digital pulse communication systems. The latter group is represented by phased array antenna control by optical signals, microwave delay lines using optical fiber and microwave switching by optical signals. These technologies mainly been researched

- DEVICE
  - Photonic signal control by Microwave
    - Modulators, Photonic Switch
  - Microwave signal control by Photonic
    - Array Antenna
    - Microwave Switch
    - Microwave Delay lines using Optical Fiber
- SYSTEM APPLICATIONS
  - Communication Systems
    - Digital Transmission Systems
      - Closed Space Applications
        - FTTH:Fiber to the Home
        - High-speed Digital Transmission
        - Photonic LAN / FDDI
      - Open Space Applications
        - Photonic Wireless LAN / IrDA
        - Inter-satellite Optical Link
    - Analog Transmission
      - Closed Space Applications
        - CATV:Cable Television
        - Optical Exchange / All Photonic Networks
      - Open Space Applications
        - FTTA: Fiber to the Air System
        - Fiber-optic Micro cellular Radio Link
        - Radio LAN/WAN on fibers
  - Other Applications

Fig.1 Optomicrowave interaction research and applications.

by microwave engineers. Products of this research have been applied to radio signal transmission on fiber optics and are divided by closed and open space applications. These application areas and research items are summarized in Fig.1.

2.2 Application Activities of Radio on Fiber Technologies

There are several activities in progress related to opto microwave interaction devices and their system applications [1]-[20]. This section mainly reviews communication system applications. Figure 2 summarizes the research activities in radio on fiber transmission technologies.

From the early stages of optical transmission research in 1970, analog video signal transmission on fibers were researched to develop optical CATV and analog type Broadband ISDN systems. In these systems, video signals were subcarrier multiplexed in radio frequency and directly modulated optical signal intensity. Accordingly, the technology is called Sub Carrier Multiplexing (SCM). These activities are summarized in the special issue of IEEE JSAC [1].

Later, LSI technologies rapidly progressed and sophisticated digital signal processing became available. From that point, analog video signals could be easily converted to a compressed digital signal format and multiplexed in a digital pulse.

Subsequently, SCM technologies were refined and improved to expand the operation bandwidth and applied to microwave signal transmission through fiber. The first application was a remote antenna feeder for satellite systems that could achieve interference reduction among the satellite earth station and terrestrial radio systems. This was the first open space application of radio through fiber optics.

Recently, the rapid growth of mobile communication users has necessitated a micro/pico cell technology that requires many mobile base stations; this technology has resulted in the remote antenna application for shadowing regions. Since 1990, many research labs have published their activities, system designs and experimental results on this topic. Microwave on fiber technologies have been applied in underground free spaces and tunnels, and will be expanded to microcellular applications [11]-[17]. Several other applications are now being researched. These include personal handy phone intercell connections, FPLMTS system area expansions, high-speed subscriber loop distribution systems using millimeter-wave, CATV radio systems and Wireless WAN. We call these applications FTTA: Fiber to the Air systems or CATA: Cable to the Air systems.

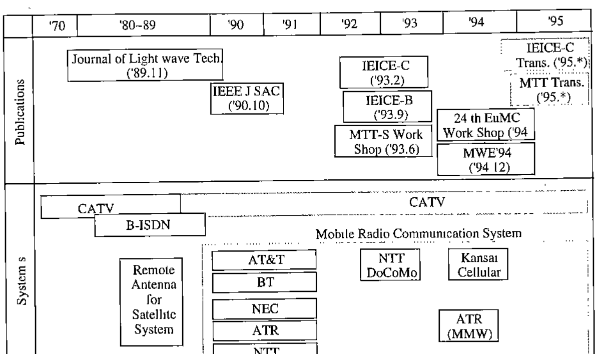


Fig.2 R&D activities concerning with the radio on fiber transmission.

2.3 Trends in Microwave and Optical Interaction Devices

Microwave and photonic interaction devices have been researched since before work began on communication applications, and have improved in step with the progress made in photonic devices. The present status of microwave/millimeter wave and photonic interaction devices is summarized in the following section.

(a) Optical Sources

For the advantages of system simplicity and outdoor use, laser diodes (LD) have become widely used. Among analog video applications, DFB-LD with isolator has been selected to reduce RIN and reflected signal beat noise.

(b) Optical Modulators

Direct optical signal intensity modulation is widely used for microwave on fiber applications, and the maximum frequency is determined by the frequency response of LD. 35 and 45 GHz have been achieved in experimental demonstrations, and more than 18 GHz has been achieved with commercial products. External modulators will be also applicable for high frequency applications. $LiNbO_3$, Pokkers, F-K and MQW types achieve more than 50 GHz.

(c) Photo-detectors

Photo diodes, such as pin-PD (~40 GHz), APD (~80 GHz), SBD (~100 GHz) and MSM (~100 GHz), and also Photo Transistors, such as MESFET, HEMT, and HBT are applicable. Usually, pin-PD is widely used for its low noise feature and OE-IC simplicity. Recently, the travelling wave photo diode (TWPD) and the wave guide type photo diode (WGPD) have been investigated and show more than 100 GHz maximum frequency.

For all of the above devices, DFB-LD with direct intensity modulation and pin-PD will be widely used at less than a several 10 GHz .

3. Present Status of Fiber-Optic Microcellular Radio

3.1 Problems of Micro/Pico Cellular Mobile Radio

Recently, mobile communication services have progressed, and the number of mobile subscribers is increasing rapidly. However, the radio frequency bands are not sufficient to satisfy these subscriber needs. To solve this requirement, it has been proposed that the cell size be reduced and the frequency reuse factor be enhanced. This technology is called micro/pico cellular technology, and it is being put into commercial use.

Another trend is multimedia expansion of mobile radio, which is called mobile computing and mobile video services. To satisfy these needs, a high speed data rate is required corresponding to video and high resolution pictures; this will require a wide frequency bandwidth, resulting in use of higher carrier frequency. It also reduces cell size because of the radio propagation losses.

These micro/pico cellular technologies will pose the following new problems in near future.
(a) Wide area service requires many radio base stations and backyard access network resources.
(b) Future new service will require many new radio base stations, long implementation time and a large investment.
(c) Traffic peak factor will increase as the traffic is distributed nonuniformly and time-varying. These traffic peaks require excess base station equipment compared with the wide area cellular system.

3.2 FREx Link Solution

To solve the above micro/pico-cell problems, one possible solution is the Fiber and Radio Extension Link (FREx Link) (Fig.3). The system uses microwave and photonic interaction devices to connect the microcell and radio control center. In this system, mobile base stations at the cell site are connected to a control station by this FREx Link [14]-[21].

It can carry cell site radio signals to the control station, keeping the radio signal format, and carry any type of cell site radio signal with the same FREx Link. Using this link, a new service can be installed in existing base stations and back yard access links, so wide and seamless new service can be started if one transceiver is installed in the control station. So the second problem mentioned before can be cleared. The third problem of needing excess transceivers to absorb nonuniform traffic can be solved by installing excess transceivers at the control station and switching them to the appropriate cells during peak traffic conditions.

3.3 Millimeter Wave-Over-Fiber Technologies

In radio links, the millimeter wave (MMW) has several attractive features beyond those offered by microwave or UHF waves;
(a) wide frequency bandwidth is available;
(b) both penetration losses through walls and diffraction losses are large, which gives compact and well defined cell boundaries; and,
(c) small wavelength can miniaturize the size of components and antennas.

Advantage (a) enables us to solve the shortage of frequency bandwidth in existing systems for high-speed mobile communications. Advantage (b) is especially benificial for micro / pico cellular or wireless LAN systems. Small size (advantage (c)) is very important for portable sets and base station facilities, which are required to be in huge numbers and easily installed. The cost and efficiency of MMW components will be improved considering the progress in MMIC and OEIC technologies. The performances of optical devices in MMW band are shown in Sect. 2.3.

On the other hand, MMW suffers large rain attenuation in outdoor use, which is, for example, about 10 ~ 20 dB/km at 50 mm/hr rain intensity. Considering a micro /pico cell system whose cell radius is less than 100 m, rain attenuation is about 1 ~ 2 dB. The outage probability corresponding to 50 mm/hr rain is less than 0.1 % of the time. Therefore, outages are negligible in mobile communications.

Wideband and low loss characteristics of an optical fiber link can most effectively extract the advantages of MMW. Several approaches exist to use MMW in a wireless link:
(1) directly sending MMW over fiber (MMW-over-fiber);
(2) sending a low frequency signal for up-conversion at the receiver end; and,
(3) optical heterodyne scheme using two coherent laser sources.

Approach (1) is the most simple method with optical carriers modulated by an MMW subcarrier. Approach (2) requires more components, which is not feasible for making compact base stations. Approach (3) is more complex and expensive to implement using conventional technology. Recent technologies related to MMW are summarized in [22]. An MMW-over fiber system requires high frequency E/O and O/E devices. An ordinary optical fiber communications system uses a huge wide bandwidth from DC to several GHz. On the other hand, MMW-over-fiber system only needs very narrow bandwidth though the subcarrier frequency is very high. Making use of this feature, performances of E/O or O/E devices can be improved by tuning their impedances only to subcarrier frequency [23].

MMW-over-fiber system was demonstrated at 43.75 GHz using FM video signal transmission [24]. Good performance was confirmed with a several 10 m radius cell. 35 Mbps QPSK digital signal transmission test was also conducted with subcarrier frequency of 43.75 GHz. Figure 4 shows measured BER performances of fiber optic link including EOM and PD using 1.3 um wavelength. This figure shows the theoretical values for QPSK and the performance when transmitting and receiving modems are directly con-

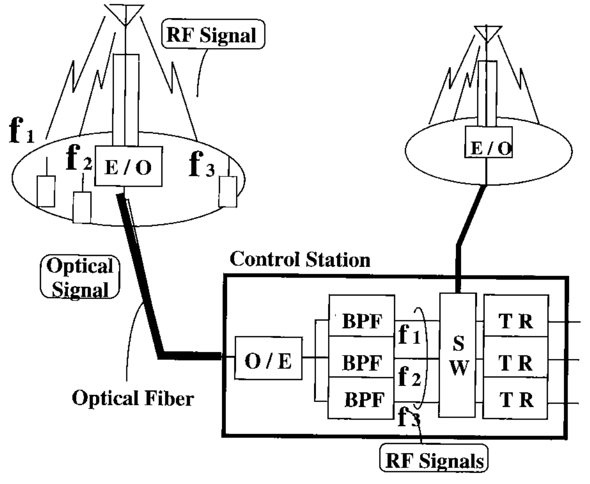


Fig.3 Fiber and radio extension link (FREx Link).

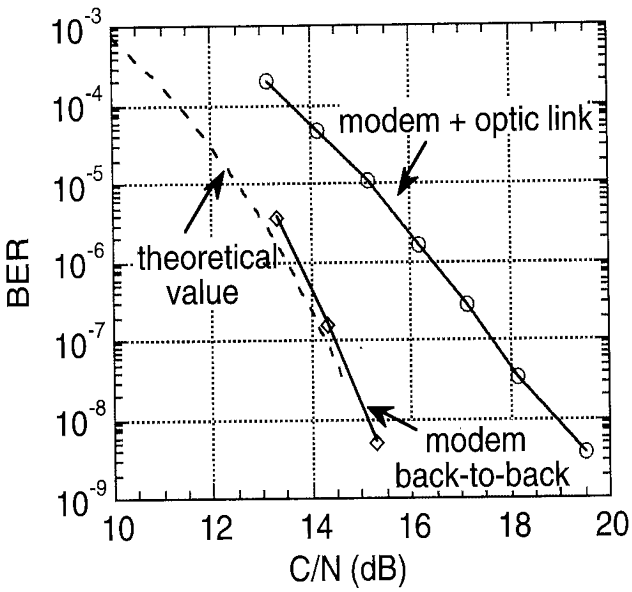


Fig.4 BER characteristics of fiber optic link for 35 Mbps QPSK digital signals.

nected. At the BER performance of 10^{-5}, the measured results shows that CNR is degradated by 2 dB in fiber optic link and requires more than 15 dB.

An MMW-over-fiber system usually needs an EOM. To simplify the system, a direct conversion method from data to bi-phase MMW modulated optical signal was proposed [26].

Recently, CDMA using spread spectrum modulation has drawn attention in mobile communications for its flexibility and robustness to multipath fading. Because CDMA essentially requires a wide frequency band to sufficiently extract its benifits, MMW is also very attractive [26].

4. Future Prospect and Proposals

4.1 Proposal for Radio Highway Networks

The FREx Link described above will be extended to the Radio Highway Network Concept illustrated in Fig.5. The system is constructed by an optical link and optical routing nodes. Here, the optical link is different from the conventional digital optical link, and constructed by the FREx link. Optical routing nodes are constructed by the optical switches. In the system, radio signals transmitted by the portable radio terminals are encapsulated into the optical signal envelopes and transferred to the appropriate remote radio control station via several optic routing switches. This is realizable by various methods shown in Sect. 4.2. The received optical envelope is decapsulated to the radio signals. Consequently, the system can open the radio free space from any cell to any cell and can switch the radio free space instantaneously according to the demands of the mobile user or service provider. We call this space as "Virtual Radio Free Space" , and the system is named as "Radio Highway

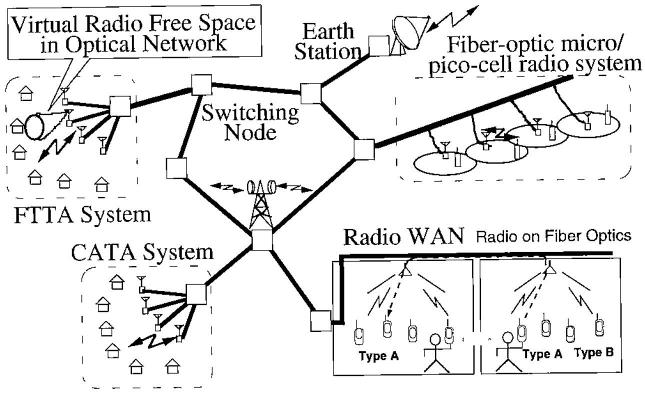


Fig. 5 Concept of the Radio Highway.

Networks" [27]-[29].

This network can be flexibly used for any type of air interface, because the virtual space can be opened from any place to any place. Therefore, any new radio service can be started without replacing radio base stations and back yard access networks, except for only one new transceiver added to one control station. Using this universal infrastructure of the Radio Highway, we can immediately start any new seamless multimedia-personal services on a global scale.

Radio Highway Networks are also applicable to indoor multimedia network, such as data, voice and video communications. It can support any radio LAN air interface working in VHF, UHF or a millimeter wave band. It also realizes full seamless connection capability from any room to any room, even if the room uses a different type of radio LAN system. We call this "Radio WAN".

4.2 Proposal for TDMA Type Radio Highway Network

There are many methods to realize the Radio Highway Networks proposed in the previous section such as TDMA, FDMA, WDM, CDMA and SDMA, which are related to time, frequency, wave length, code and space. These multiple access methods are performed both in optic and/or radio stage. Therefore, there are many cross-products among them. In Table 1, various optical stage access methods are compared. In the following section, we will analyze the optical TDMA type Radio Highway illustrated in Fig.6 [27]-[32].

Radio signal transmitted from a mobile terminal is received at the radio base stations, and the received signal directly modulates the laser diode to obtain an intensity modulated (IM) optical signal. The IM signal is fed into the optical fiber through an optical switch and is sampled in the optical stage. In the fiber, many PAM/IM signals are multiplexed from many radio base stations by the TDMA method. These signals are transmitted to one of the optical switching nodes. Every PAM/IM signal is routed to their destined radio control station. At the destined station, the received optical PAM/IM signal is detected by the photodiode, and then radio PAM signals are obtained. Using appropriate bandpass

Table 1 Comparison among various access methods on fiber.

Access Method	Function	Features
TDMA	Optical Time Division Multiple Access	High speed and linear photonic swichs are required Loss-less duplexing is available.
WDM	Wave Length Division Maltiple Access	A lot of wavelength are required when many base stations exist in the same bus line.
FDMA	Optical Frequency Division Multiple Access	Highly stabilied LD and Optical Frequency Duplexers are requirwd.
CDMA	Optical Code Division Multiple Access	High speed code synchronization on optical stage is required
SDMA	Space Division Multiple Access	Not fits for Optical Fiber Transmission.

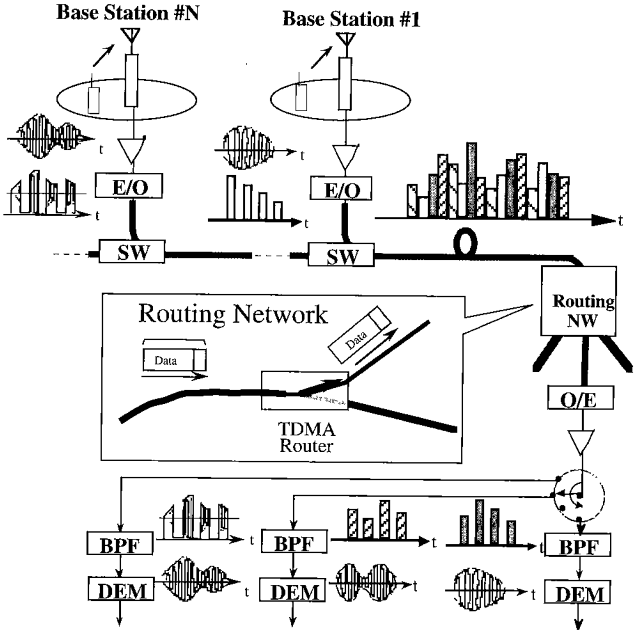


Fig.6 TDMA type radio highway networks.

filtering, the detected PAM radio signal is converted to the actual continuous radio signals. In this paper, synchronous time division multiplexing is illustrated; however, asynchronous multiplexing is applicable for simplifying the synchronous operation [32]. Several optical network routing algorithms can be considered, and the digital asynchronous cell header will have a high compatibility with the existing ATM switch. The required sampling frequency is at least double that of the symbol rates or radio bandwidth and relatively very low compared with a doubled carrier frequency [27]. The carrier frequency and phase can be sustained in the PAM signal, so it is not necessary to transmit this information.

This TDMA networks not only have network universality, but also other distinctive features. One advantage is that the system has more handling capacity compared with the conventional SCM. In the SCM, laser diode nonlinearity produces intermodulation products among subcarriers. On the other hand, the TDMA system has rather smaller signals in radio frequency, so the intermodulations are relatively small compared with the conventional systems. Available

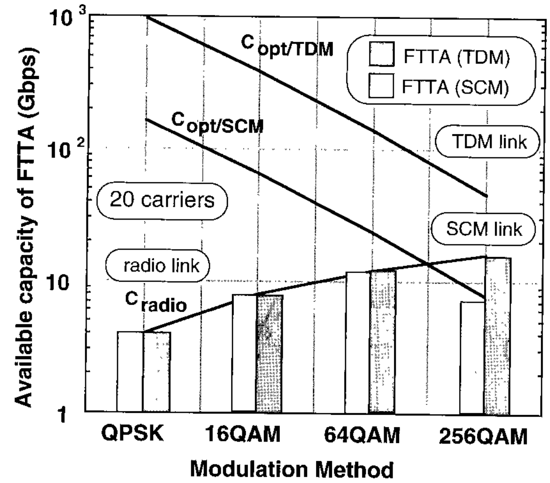
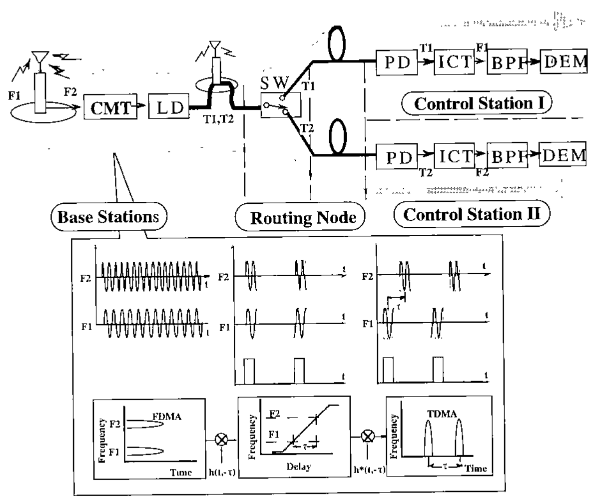


Fig.7 Available capacity of the TDMA type radio highway.

capacity of the TDMA system is calculated with consideration to modulation types of the radio signal, and the results are shown in Fig.7. In the analysis, FTTA: Fiber to the Air System working in the 50GHz band is assumed [18]. The available capacity was more than 18 Gb/s, which is about 6 times greater than the conventional SCM.

4.3 Proposal for Chirp multiplexing type Radio Highway Networks

In the TDMA type Radio Highway networks, different types of radio signals in the same cell at the same time cannot be divided, so these signals reach the same destination. However, it is better for different types of radio signals in the same cell at the same time to reach different destinations because different types of radio signals are usually operated by the different service points and providers. For these requirements, chirp multiplexing type Radio Highway Networks is proposed [29]-[31]. Figure 8 illustrates the configuration and principle of the chirp multiplexing type Radio Highway Networks. The operation principle is described as follows. In this example, there are two service providers; one uses the F_1 frequency band and the other uses the F_2 frequency band, such as F_1 is 800 MHz and F_2 is 1.8 GHz. Radio signals transmitted from two mobile terminals are received at the same base station at the same time. These signals are chirp transformed at the electrical stage or photonic stage. After chirp transform, frequency division multiple access signals are converted to the time division multiple access signals as shown in the figure. Higher frequency band signal F_1 delays τ longer compared with the lower frequency band signal F_2. Finally, we obtain IM/PAM/TDM optical pulses. They are transmitted with a digital header that recognizes the initial and destination base station cell numbers. Then, the routing nodes detect the header pulses and a faster burst T_1 is switched over to the control station that is operating in the F_1 frequency band, and after the τ delay time routing switch turns over to the control station that is operating in the F_2



Chirp Multiplexing

Fig.8 Chirp multiplexing type radio highway networks.

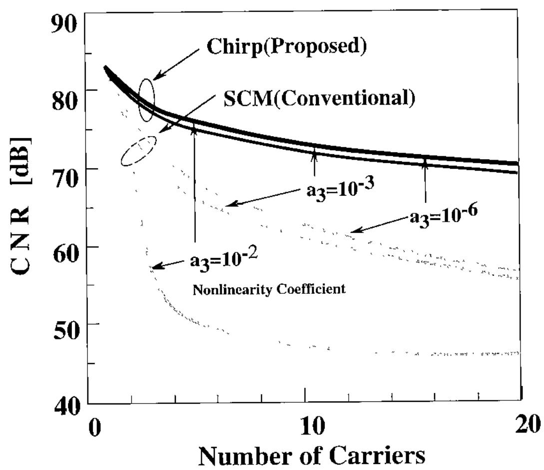


Fig.9 CNR improvement of chirp multiplexing type radio highway networks.

frequency band.

The proposed system can realize universal and flexible networks for multiband/multicarrier services. At the same time, it has other distinctive features. This system has a good carrier to noise power ratio (*CNR*) compared with the conventional SCM as illustrated in Fig.9. In the figure, parameter a_3 shows the third order nonlinearity coefficient of the laser diode, which is a dominant factor of intermodulation noise. From the results of this calculation, the proposed system is free from nonlinearity and can improve the handling number of radio carriers.

5. Conclusion

This paper reviewed the present status of research and development activities in Optomicrowave Interaction devices and applications. It also proposes some new concepts. This technology is very effective in universal radio access networks for future multimedia and high speed radio communication systems. Millimeterwave-over-fiber technologies were found to enable us to solve the shortage of frequency band width.

In the final section, we proposed the TDMA and Chirp Multiplexing Radio Highway Networks and gave some numerical results. This network can open the Virtual Radio Freespace from any place to any place depending on demand.

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References

[1] "Applications of RF and Microwave Subcarriers to Optical Fiber Transmission in Present and Future Broadband Networks," IEEE Journal on Selected Area in Comm., vol.8, no.7, Sept. 1990.

[2] "Special Issue on Optical/Microwave Interaction Devices, Circuits and Systems," IEICE Trans. Electron., vol.E76-C, no.2, Feb 1993.

[3] "Wireless Communications via Lightwave," MTT-S Workshop WSMF, June 1993.

[4] "Special Issue on Fiber-optic Microcellular Radio Communication System and their Technologies," IEICE Trans. Commun., vol.E76-B, no.9, Sept. 1993.

[5] "Workshop1: Ortical/microwave and millimeter-wave technologies," MWE'93, Sept. 1993.

[6] "Work Shop 1: From Microwaves to Optics," 24th European Microwave Conf., Sept. 1994.

[7] "Special Issue /on Microwave and Millimeter-wave Photonics," IEEE Trans. MTT, vol.MTT-43, no.9, Sept. 1995.

[8] W.I.Way, "Subcarrier multiplexed light wave system design considerations for subscriber loop applications," IEEE Journal of Lightwave Tech., vol.7, no.11, pp.1806-1818, Nov. 1989.

[9] M.Akaike, "Trends of research on microwaves/optics in Japan," Proc. 24th European Conf., Sept. 1994.

[10] P.Cochrane, R.Heckingbottom, and D.Heartley, "The hidden benefits of optical transparency," IEEE Commun. Mag., pp.90-97, Sept. 1994.

[11] L.J.Mayer, "Using fiber optics with analog RF signals," Proc. 39th IEEE Veh. Tech. Conf., June 1989.

[12] A.J.Cooper, "Fiber/radio for the provision of cordless/mobile telephony services in the access network," Electronics Letter, vol.26, no.24, pp.2054-2056, Nov. 1990.

[13] T.S.Chu and M.J.Gans, "Fiber optic microcellular radio," Proc. IEEE Veh. Tech. Conf., pp.339-344, May 1991.

[14] Shibutani et al., "Microcell mobile radio access method using radio on fiber transmission," IEICE Technical Report, RCS46-8, Jan. 1990. or in Proc. ICC'91, pp.1176-1181, June 1991.

[15] H.Otsuka et al., "Subcarrier transmission approach to microcellular systems," Proc. ICC'92, pp.82-86, 1992.

[16] H.Ogawa et al., "Fiber optic millimeterwave link for personal mobile radio system," Autum Natl. Conv. Rec. IEICE Japan, B-736, Sept. 1990, or in IEEE Trans. MTT, vol. MTT-40,

pp.2285-2293, Dec. 1992.
[17] R.Ohmoto et al., "Performance of p/4QPSK signal transmission on optical fiber," Autum Natl. Conv. Rec. IEICE Japan, B-277, Sept. 1991.
[18] S.Komaki, K.Tsukamoto, S.Hara, and N.Morinaga, "Proposal of fiber and radio extension link for future personal communications," Microwave and Optical Technology Letters, vol.6, no.1, pp.55-60, Jan. 1993.
[19] H.Harada, H.J.Lee, S.Komaki, and N.Morinaga, "Performance analysis of fiber-optic millimeter-wave band radio subscriber loop," IEICE Trans. commun., vol.E76-B, no.9, pp.1128-1135, Sept. 1993.
[20] H.Mizuguti, S.Komaki, and N.Morinaga, "Performance analysis of fiber optic link for microcellular mobile communication systems," IEICE Trans. Electron.,vol.E76-C, no.2, pp.271-278, Feb. 1993.
[21] T.Okuno, H.Mizuguti, S.Komaki, and N.Morinaga, "A new frequency switching/IM3 reduction method in fiber optic microcellular system," IEICE Trans. commun., vol.E76-B, no.9, pp.1178-1184, Sept. 1993.
[22] R.P.Braun, G.Grosskopf, and D.Rohde, "Optical millimeter-wave generation and transmission technologies for mobile communications, an overview," Proc. 1995 IEEE Microwave System Conf., pp.239-242, May 1995.
[23] H.Kawamura, E.Suematsu, and N.Imai, "A 45-50 GHz monolithic integrated HEMT/MSM OEIC receiver," Proc. 25th European Microwave Conf., Sept. 1995.
[24] N.Imai, H.Kawamura, E.Suematsu, and E.Ogawa, "Millimeter wave personal communications system using fiber-optic links," Proc. 1994 IEEE MTT-S Topical Meeting on Optical Microwave Interactions, pp.141-144, Nov. 1994.
[25] H.J.Thomas, N.Imai, and E.Ogawa, "An optical bi-phase modulator for millimeter wave subcarrier systems," IEICE Trans. Electron., vol.E79-C, no.1, pp.32-39, Jan. 1996.
[26] H.J.Thomas and H.Ogawa, "Indoor millimeter wave PCN/LAN experiment based on direct MMW distribution over optical fiber and multi-path robust spread spectrum modulation," Proc. 1993 IEEE VTC, pp.236-240, May 1993.
[27] S.Komaki, K.Tsukamoto, M.Okada, and H.Harada, "Proposal of radio high-way networks for future multimedia-personal wireless communications," Proc. ICPWC'94, Bangalole, India, pp.204-208, Aug. 1994.
[28] S.Komaki et al., "Network considerations on fiber-optic microcellular radio systems," Proc. 24th European Microwave Conference Work Shop, Canne, France, pp.46-51, Sept. 1994.
[29] S.Komaki, K.Tsukamoto, and M.Okada, "Multiband operation of multimedia mobile radio on virtual radio free space network," Proc. Mobile Multimedia Commun. '95, Bristol, UK, S.3.5, April 1995.
[30] H.Harada, K.Tsukamoto, M.Okada, S.Komaki, and N.Morinaga, "Microcellular radio communication system with TDMA fiber optic link," IEICE Trans., vol.J77-C-I, no.11, pp.649-658, 1994.
[31] K.Tsukamoto et al., "TDM intercell connection fiber-optic link for personal radio communication systems," Proc. Asia-Pacific Microwave Conference '94, Tokyo, Japan, pp.1039-1042, Dec. 1994.
[32] Y.Shoji et al., "Considerations on asynchronous multiple access scheme for optical fiber radio-highway networks," IEICE Technical Report, RCS95-29, May 1995.
[33] J. Sumasu et. al., "Optical fiber radio-highway networks using chirp multiplexing method," Natl. Conv. Rec. IEICE Japan, B-551, March 1995.

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